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BROADBAND SEISMIC CHARACTERIZATION OF THE ARABIAN SHIELD

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A temporary deployment of eight broadband seismographs in the Arabian Shield and one on the Arabian Platform has shown that the shield sites are among the quietest in the world, with noise levels generally only slightly above the low-noise model. Distinct path-related differences in the recording of regional events allow the assignment of general source regions upon mere visual examination of the recordings. To date, clear regional phases are observed on intra-Arabian Plate paths from events in the Zagros region. Events occurring in the Gulf of Aqaba and propagating mostly in the Arabian Shield show a clear but weak P_n phase and prominent L_g. Events originating in the Arabian Sea show clear body waves but no L_g.

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Introduction

This annual report covers the first year of a two-year project to operate broadband seismographs in the Arabian Shield. The project has been a cooperative project of the University of California at San Diego (UCSD), Boise State University (BSU), and King Saud University. The King Abdul Aziz City of Science and Technology has provided major assistance and facilities for the project.

The main goal of the first year was simply to get some instruments operational and collect some data. Because of the way the data flow has been managed, only the UCSD group has had the opportunity to seriously work with the data collected to date. A general release of data has now been arranged through the IRIS Data Management Center and so it is now possible for other investigators to begin examining data. Since BSU somehow fell into the "other" category we are only now obtaining and beginning to examine the data. Therefore, this report will concentrate on a brief description of the operation of the Saudi Arabia deployment to date and then discuss some of the results that either UCSD has already reported or else that are evident from cursory examination of the data. Finally, our own plans for the second year of the project will be discussed.

Significance of the Project

Despite the strategic location of Saudi Arabia, the presence of a large area of shield rocks, and the expected low background noise levels, ours was the first joint Saudi-USA project to deploy broadband seismographs whose data will be widely available. As a result, we are collecting a unique data set for regional seismic characterization purposes as well as investigations related to monitoring the proposed Comprehensive Nuclear Test Ban Treaty.

Operation of the Saudi Arabia Broadband Deployment

Broadband seismograph installation in Saudi Arabia began in late November 1995, with installation of a station near the now-operational GSN station at Ar Rayn. All stations except one (Riyadh) have been sited on rocks of the Arabian Shield. Riyadh is situated on the Arabian Platform, which is composed of nearly flat-lying sedimentary formations. Site selection was

made by UCSD personnel, with an attempt to locate stations generally along a line near the 1979 USGS refraction profile. Vault preparation was overseen by BSU. Although it had been planned that the initial installations would be done jointly by UCSD and BSU, delays in getting equipment passed by Saudi customs led to installation being primarily a UCSD project. The Saudis and UCSD have maintained the network. Figure 1 shows the initial network configuration, and Table 1 gives the location of the stations occupied to date.

Although the first stations were installed in late November 1995, hard disk problems and the theft of a data acquisition system have led to significantly less than 100% data recovery. Seismometer problems compromised the broadband response at one station until discovered and corrected. Nevertheless, a large body of significant data has been recorded. As of this writing (late September 1996) the stations are still operational, although it will be necessary to close them and return the equipment to the United States in the near future.

Preliminary Results

A summary of the early results has been presented by Vernon *et al.* (1996); this paper is reproduced as Appendix 1. Briefly, the Saudi stations are among the quietest sites in the world in the 1 - 10 Hz frequency band, as was expected. Noise levels approach or equal the low-noise model at essentially all sites. A detection threshold near m_b 3.5 is observed at all stations for events in the 10 - 100° distance range. It should be noted that this detection threshold is with respect to magnitudes reported in the Reviewed Event Bulletin (REB) of the Center for Monitoring Research; these magnitudes usually are lower than those reported in Preliminary Determination of Epicenters.

Seismograms of regional events at epicentral distances of about 10° display major variations in character depending upon the events' source regions. Events originating in the Gulf of Aqaba to the northwest of the deployment show large, clear L_g arrivals, small P_n and S_n phases and little or no evidence of other crustal phases. Shallow events from the Arabian Sea to the southeast of the deployment exhibit clear body and surface waves but no L_g motion. Zagros events to the

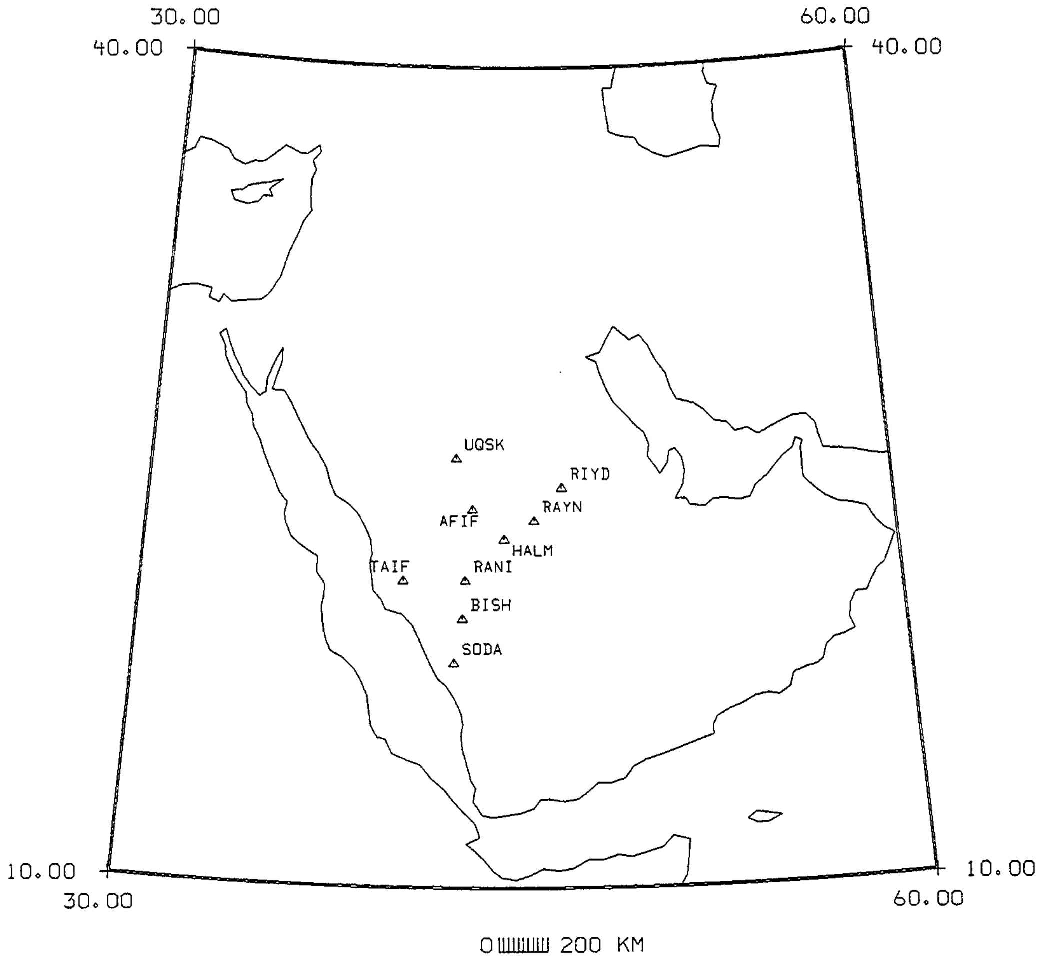

Figure 1. Broadband Sites

TABLE 1: BROADBAND STATION SITES

Code	N Latitude dg mn sec	E Longitude dg mn sec	Elevation km	Site
AFIF	23 55 51.60	43 02 24.00	1.116	Afif
BISH	19 55 22.10	42 41 24.40	1.379	Bisha
HALM	22 50 43.40	44 19 02.30	0.930	Hadabat Al-Mahri
RANI	21 18 41.80	42 46 34.00	1.001	Raniyah
RAYN	23 31 19.20	45 30 02.90	0.792	Ar-Rayn
RIYD	24 43 19.20	46 38 34.80	0.717	Riyadh
SODA	18 17 31.60	42 22 36.80	2.876	Al-Soda
TAIF	21 16 51.60	40 20 56.40	2.050	Taif
UQSK	25 47 20.40	42 21 36.00	0.950	Uqlat As Suqur

northeast of the deployment show clear P_n and S_n arrivals as well as secondary phases and L_g. Shallow Zagros events are also characterized by a nice dispersed surface wave train. As a result of these regional differences in event character, it is simple to deduce the source region of a shallow event merely by visual examination of a seismogram.

There are some geological correlations with these observations. Gulf of Aqaba events are occurring in a rift environment near the south end of the Dead Sea Rift, but the propagation path is mainly through shield rocks. It is not clear at this time just why the P_n and L_g phases are so differently recorded as a result of this mixed path. A more directly explained situation is that of the Zagros events, which are occurring in the underthrusting part of the Arabian Plate (Jackson and Fitch, 1981) and thus have entirely intra-plate paths to Arabian Shield sites. As expected, propagation of regional phases is efficient for such paths. Finally, Arabian Sea events have mixed paths beginning and having a large component in oceanic crust, and regional phases are not observed.

On a more local scale, we have noticed from recorded seismograms of the KACST short-period telemetered network that high frequency (~10 Hz) L_g propagation appears to be extremely efficient within a couple of hundred kilometers of the Gulf of Aqaba. Short-period vertical seismograms from this region are reminiscent of those recorded in high Q areas like the central United States. KACST stations in southwest Saudi Arabia near the Yemen border appear to have lower Q, although no definitive study has yet been performed. It is interesting to speculate on the geologic reason for efficient L_g propagation from the Gulf of Aqaba events, when body phases appear to be weak and severely attenuated.

Future Plans

With data now being available, some quantitative studies are possible. Our interests are in propagation of regional phases, with particular emphasis on recordings of depth-dependent phases such as P_mP. Shallow Zagros events are the most interesting recorded to date in terms of observable regional phases. We will model the travel times expected along our deployment for

events reported in the REB, and attempt to identify depth-dependent phases. If any events have well-constrained focal depths based on teleseismic depth phases, we will also attempt empirical identification of depth phases that may not be predicted by the regional crustal model; we have recently had better success with such methodology in the northwestern USA than with the more direct forward modeling approach (Zollweg and Childs, 1996).

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Jackson, J., and T. Fitch (1981), Basement faulting and the focal depths of the larger earthquakes in the Zagros mountains (Iran), *Geophysical Journal of the Royal Astronomical Society* **64**, 561-586.

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APPENDIX

Initial Results from the Deployment of Broadband Seismometers in the Saudi Arabian Shield

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ABSTRACT

The preliminary results from the first six months of our field deployment of nine portable broadband stations suggest that sites in the Arabian shield are extremely quiet with ground noise near or equal to the low noise model in the frequency band from 1-10 Hz at the station RAYN. The low noise also contributes to the very low detection threshold at RAYN of events with mb = 3.5 at distances from 10 to 100 degrees. These stations appear to be among the best sites in the world for the properties of detection thresholds and ground noise levels. Seismograms from sources 10 degrees from the center of the network have very unique characteristics which can be used to identify the source regions. Zagros events have a clear Pn and Sn arrivals with an observable Lg. Shallow events from the Arabian Sea have clear P, S, and surface waves but no discernible Lg phases. From the opposite direction, aftershocks from the Gulf of Aquaba have very weak P and S waves with very strong Lg phases.

Keywords: Saudi Arabia, detection thresholds, ground noise, seismic regionalization

OBJECTIVES

This project consists of a field program in the Kingdom of Saudi Arabia to collect broadband seismic waveform data and the associated parametric data describing the sources. We currently have deployed nine portable broadband seismic stations on the Arabian Shield and plan to record over a period of about a year. Most of the regional seismic sources are in the tectonically active areas of Iran and Turkey. Other areas of seismic activity include the Red Sea Rift bordering the Shield to the southwest, the Dead Sea Transform fault zone to the north, and the Arabian Sea to the southeast.

The main research objectives of this program are:

1. to study the propagation of regional phases across the Arabian Shield over a broad band of frequencies,

2. to study the crustal structure and seismicity of the Arabian Shield,

3. to characterize potential sites for permanent seismic facility installation

RESEARCH ACCOMPLISHED

The first deployment in late 1995 consisted of 6 seismographs arranged in two linear arrays (Figure 1). One linear array consists of the stations RAYN, HALM, RANI. This profile's long axis is pointed in the direction of high seismicity in the Zagros. These earthquakes are occurring in the Arabian Plate where it is colliding with Persian Plate (Jackson and Fitch, 1981). Seismic wave ray paths along this profile from Zagros events should therefore have entirely intra-plate paths. Stations will be between 900 and 1500 km from the nearest Zagros sources. The second linear array consists of the stations AFIF, RANI, BISH, SODA. Events in the highly active area of the Afar triple junction in Africa and events in the Caucasus are also generally aligned with this alignment.

Early in the experiment the station BISH was vandalized and the station was closed. Three new stations were installed in June 1996 at TAIF, UQSK, and RIYD. These stations provide a more areal distribution that the initial deployment. The station at RAYN was converted from at portable station to a permanent GSN station in June 1996.

The array deployments will allow sampling of regional wave characteristics over a broad area, from very numerous source regions. It is reasonable to expect that ray paths traversing virtually every area of the shield will be recorded, given the high seismicity rates characteristic of most of the active areas around the shield. We expect from experience operating portable seismographs in some parts of the shield that most sites will have very low noise levels, so a variety of teleseismic signals suitable for receiver function analysis should also be obtained.

Instrumentation

Each station has a Streckeisen STS-2 broadband seismometer which has a pass band between 0.008 Hz and 50 Hz. Each seismometer is heavily insulated to protect it from the daily changes in temperature. Each sensor is attached to bedrock outcrops whenever possible.

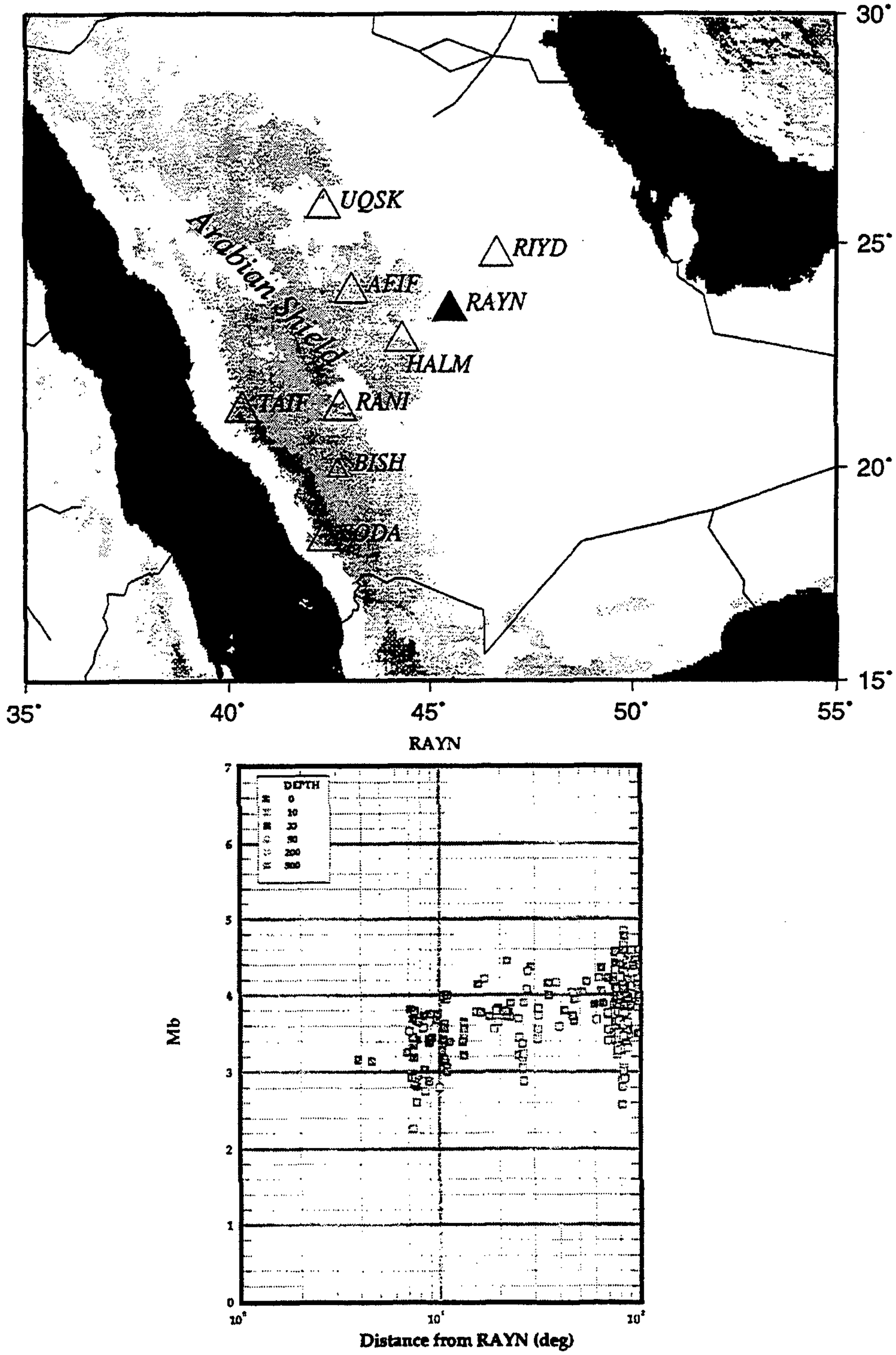

Figure 1. (top) Map of station deployment. Open triangles are temporary deployment and closed triangle is a permanent station. Light shading represents elevations above 1000 m, dark shading above 2000 m. **(bottom)** Magnitude/distance plot showing detection threshold for station RAYN.

Station	Latitude	Longitude	Elevation (Km)	Location
AFIF	23.9310	43.0400	1.1160	Afif, Saudi Arabia
BISH	19.9228	42.6901	1.3790	Bisha, Saudi Arabia
HALM	22.8454	44.3173	0.9300	Hadabat Al-Mahri, Saudi Arabia
RANI	21.3116	42.7761	1.0010	Raniyah, Saudi Arabia
RAYN	23.5220	45.5008	0.7920	Ar-Rayn, Saudi Arabia
RIYD	24.7220	46.6430	0.7170	Riyadh, Saudi Arabia
SODA	18.2921	42.3769	2.8760	Al-Soda, Saudi Arabia
TAIF	21.2810	40.3490	2.0500	Taif, Saudi Arabia
UQSK	25.7890	42.3600	0.9500	Al-Soda, Saudi Arabia

The output of the STS-2 is recorded at a sample rate of 40 sps by a 24-bit REFTEK RT72A-08 datalogger. At the station the data are stored on a 2 Gbyte SCSI disk. To take advantage of the copious amounts of sunshine available in Saudi Arabia, we use solar panels to charge car batteries. Timing to the station is provided by a local GPS clock. Data are retrieved by exchanging disks at each site during service runs. Each site is visited every four to six weeks.

Processing

The processing scheme requires several steps: raw data retrieval followed by formatting, quality control, and event association. A Sun Sparc field computer is set up in Riyadh. The data conversion to CSS 3.0 format and quality control are performed on this field computer. The data are then sent to UCSD where an automatic picking program is used to identify all arrivals. These arrivals are reviewed by an analyst. The initial event associations are based on predicted arrivals from a REB origin table using the IASPEI91 travel time tables and the actual phase picks. Any recorded events not appearing in the REB catalog are processed. The data are sectioned into an event oriented CSS 3.0 waveform database and will be distributed to interested users.

Operating at 40 samples/second continuously, each station collects 41.5 Mbytes of waveform data per day. Thus, about 250 Mbytes per day for the 6 stations will have to be processed. Assuming that there will be the equivalent of about 300 network-days of operation during the experiment, the total data produced will be on the order of 75 Gbytes.

Data

Initial processing has been started for the first six months of data. At present 367 events have been processed and are shown in lower map in Figure 2. The upper epicenter map in Figure 2 shows the 77 events within 20 degrees of the stations. Most of these events are

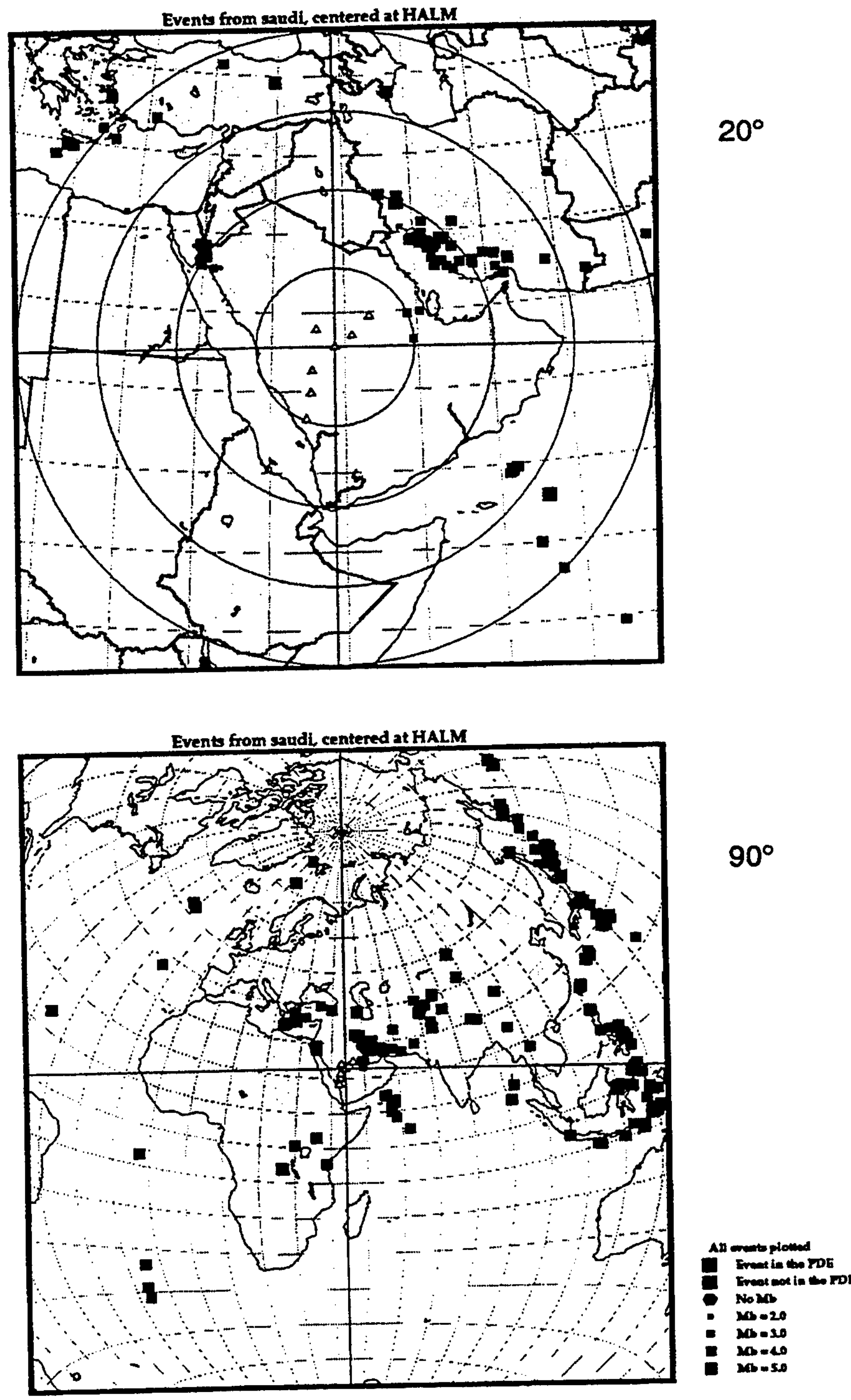

Figure 2. (Top) Map showing detected regional events for data currently processed. **(Bottom)** Regional and teleseismic events recorded by broadband deployment.

located in the Zagros region with the remaining concentrated as aftershocks to the 23 November 1995 Gulf of Aquaba earthquake or from events in the Arabian Sea. Each of these three source regions are approximately 10 degrees from the center of the network and have unique seismic characteristics. Events from Iran have a clear Pn and Sn arrivals with an observable Lg (Figure 3). Shallow events from the Arabian Sea have clear P, S, and surface waves but no Lg phases as demonstrated in Figure 3. From the opposite direction, aftershocks from the Gulf of Aquaba have very weak P and S waves with very strong Lg phases (Figure 4).

Signal and Noise Characteristics

The most important seismic characterizations is an estimate of its signal-to-noise properties of a particular site. The ambient noise spectra over a variety of conditions provides an estimate of the theoretical performance relative to other sites and to accepted noise models. A variety of near-site conditions affect the ambient noise including cultural activities, weather and wind patterns, local seismicity, and proximity to oceans/seas. The teleseismic and regional signal reception levels are affected more by regional structure than the site characteristics.

For each site we occupy, we will develop comprehensive estimates of the signal and noise characteristics over the seismic band from approximately 50 seconds to 15 Hz. An example of the seismic noise characteristics is shown in Figure 5. A short segment of data from each channel is shown for the station RAYN. The Low-Noise model is provided for comparison. The station at RAYN actually equals the Low-Noise model at 2 Hz.

Detection Thresholds

Following the method of Harvey, 1994, we will calculate for each station the single site magnitude detection thresholds. Using event m_b magnitudes reported in the REB, the m_b estimates from our data in the 0.8 to 3 Hertz pass band, will be corrected to produce zero mean statistics for the REB relative residuals.

Single site m_b vs. distance functions give us the raw information for determining single site detection magnitude thresholds. In a traditional analysis of single site detection magnitude thresholds one would create a map view, put events into regional bins, compute magnitude-frequency functions for each bin and set the magnitude threshold for each bin according to some roll-off criteria applied to the magnitude-frequency functions. However, this method requires more events than we are likely to have in our catalog.

The alternate method for determining single site detection magnitude thresholds which yields reasonable results from relatively small catalogs. The method is based upon using P wave signal to noise ratios observed at a given station to scale event magnitudes to equivalent threshold values for that station. This is done by adjusting the event magnitude by an amount equal to the logarithm of the ratio of the observed signal to noise level and a threshold signal to noise level representing the minimum level at which a signal would be detected. The assumption here is that the wave propagation is a linear process so that amplitudes can be scaled directly. This approach allows us to scale down large magnitude events to equivalent smaller events that would be at the detection limit for each particular source-receiver geometry.

The results of this method applied to the events shown in Figure 1b for a specified detection threshold signal to noise level of two. Figure 1b shows such a function produced from events for station RAYN where squares represent events that were in the REB and the

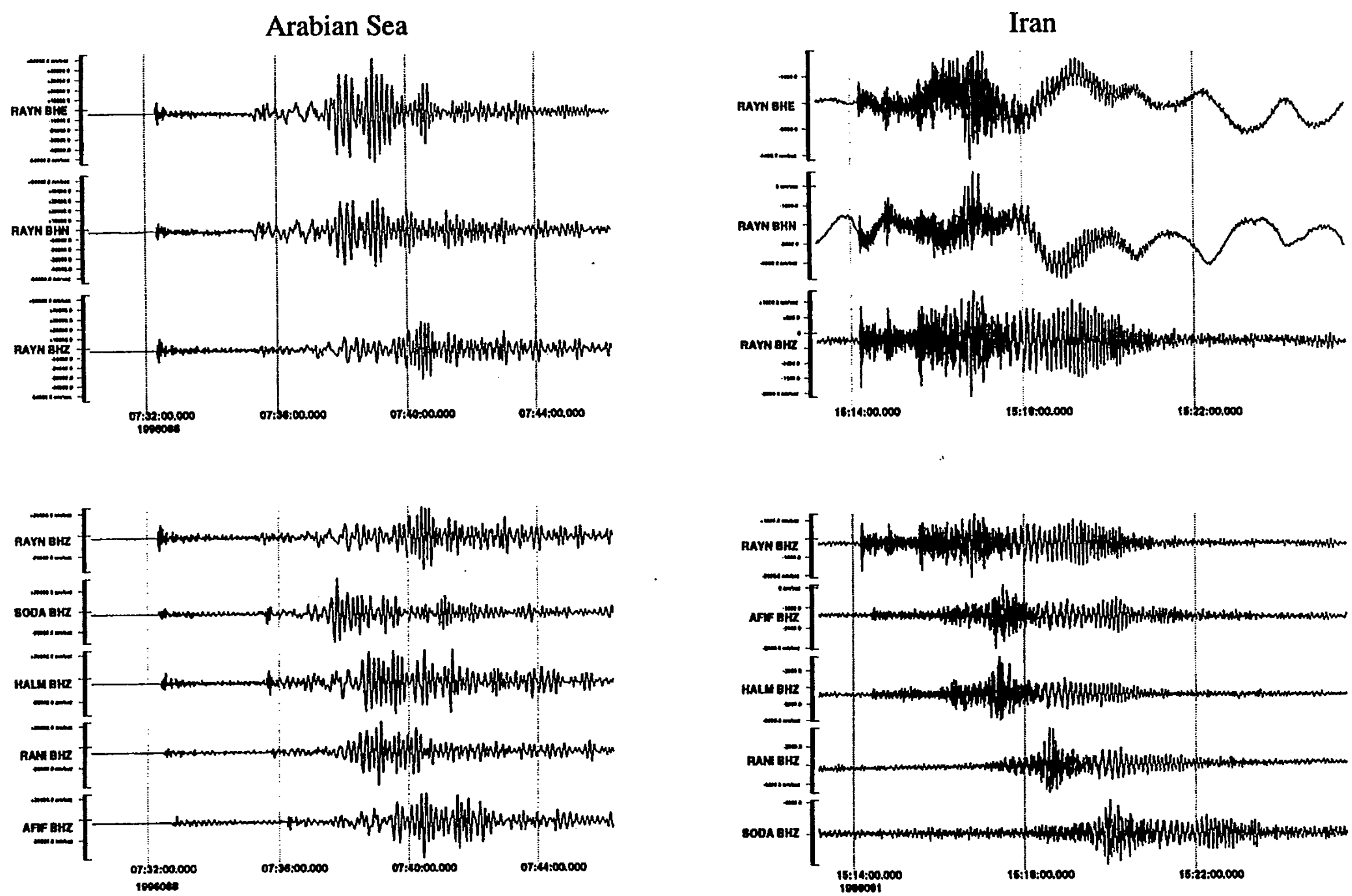

Figure 3. Two events from approximately 10° away showing vertical components for all stations (bottom) and all three components (top) for station RAYN. Note difference in regional waveforms for Mb 5.8 Arabian Sea event almost due south of network and mb 4.7 Iranian event east of network.

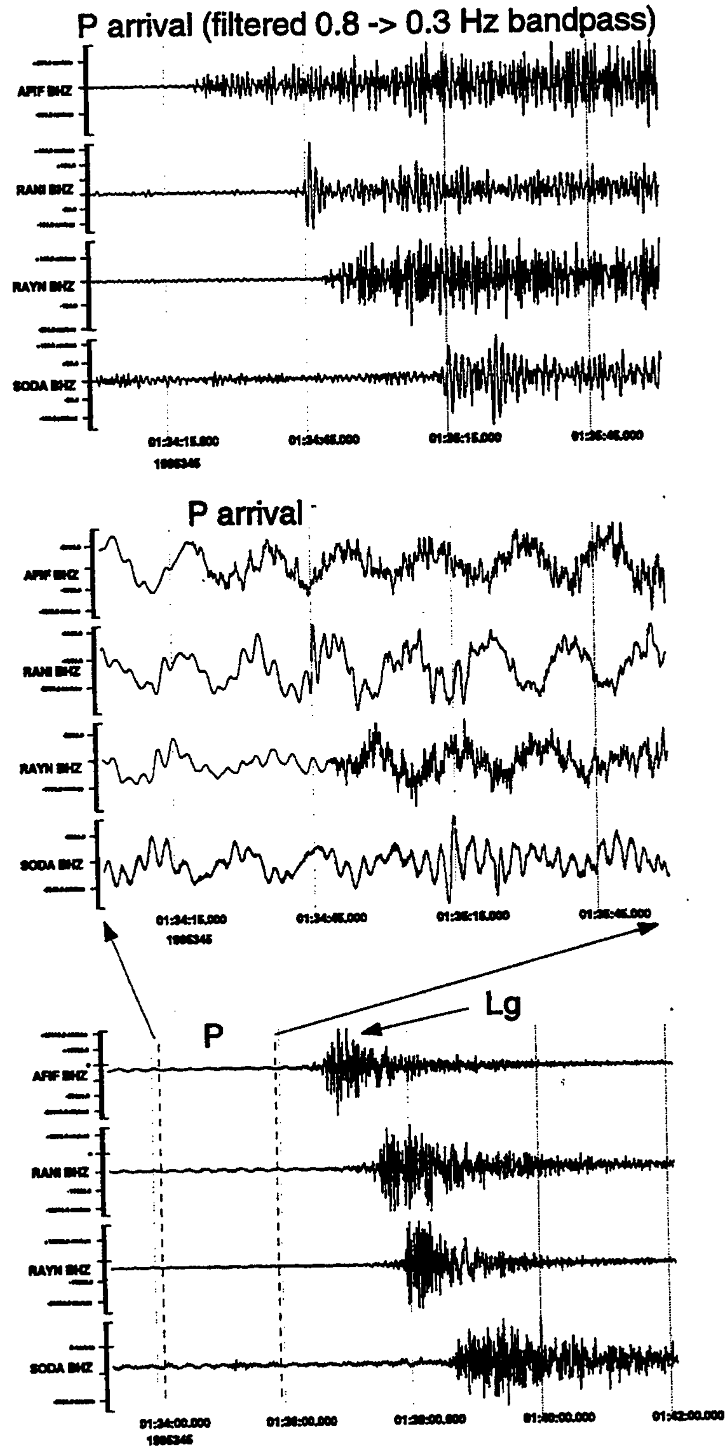

Figure 4. Mb 4.6 aftershock from the November 22 1995 Gulf of Aquaba event. Distance is approximately 8°. Note prominant Lg phase and low amplitude body phases.

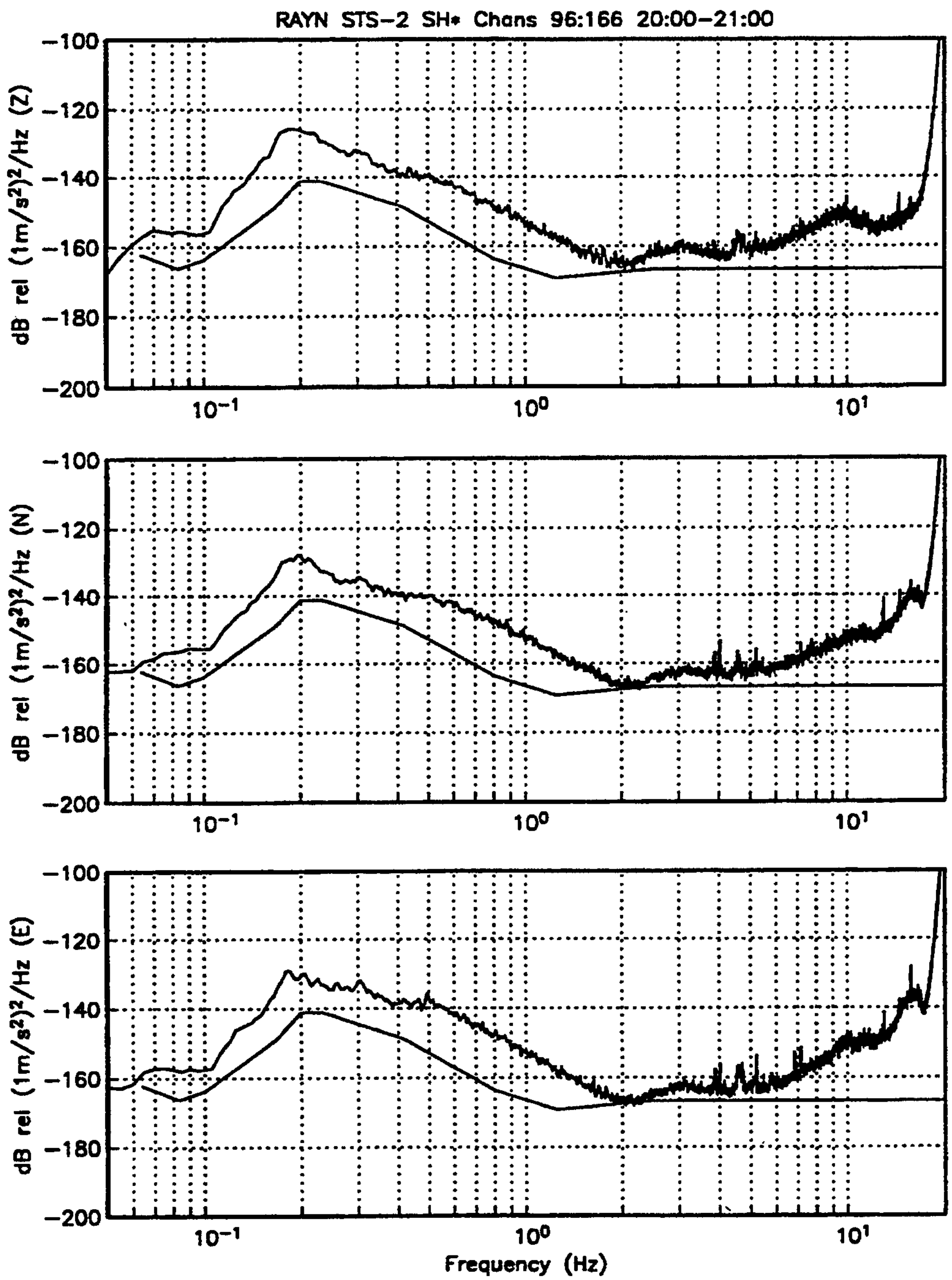

Figure 5. Acceleration power spectra for the Z, N, and E components for the station RAYN. The lower curve in each plot is the Low-Noise model.

symbols are color coded according to event depth. We can see that the populations of shallow and deep events clearly separate as one would expect. Our preliminary results show that the mb detection threshold for the distance range of 10-100 degrees is about mb = 3.5.

CONCLUSIONS AND RECOMMENDATIONS

The preliminary results of our field deployment suggest that many of our sites in the Arabian shield are extremely quiet with ground noise near or equal to the low noise model in the frequency band from 1-10 Hz. The low noise also contributes to the very low detection threshold of events with mb >= 3.5 at distances from 10 to 100 degrees. These stations appear to be among the best sites in the world for the properties of detection thresholds and ground noise levels. Seismograms from sources 10 degrees from the center of the network have very unique characteristics which can be used to identify the source regions. Zagros events have a clear Pn and Sn arrivals with an observable Lg. Shallow events from the Arabian Sea have clear P, S, and surface waves but no discernible Lg phases. From the opposite direction, aftershocks from the Gulf of Aquaba have very weak P and S waves with very strong Lg phases.

In the future the understanding of the waveform propagation properties would be enhanced by placing stations further north in the Arabian shield areas. Based on our observations, there exist several excellent sites in the shield region of Saudi Arabia which could be used for potential seismic arrays.

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